

Composite Interlaminar Shear Fracture Toughness, G_{IIC} : Shear Measurement or Sheer Myth?

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Abstract

The concept of G_{IIC} as a measure of the interlaminar shear fracture toughness of a composite material is critically examined. In particular, it is argued that the apparent G_{IIC} as typically measured is inconsistent with the original definition of shear fracture. It is shown that interlaminar shear failure actually consists of tension failures in the resin rich layers between plies followed by the coalescence of ligaments created by these failures and not the sliding of two planes relative to one another that is assumed in fracture mechanics theory. Several strain energy release rate solutions are reviewed for delamination in composite laminates and structural components where failures have been experimentally documented. Failures typically occur at a location where the mode I component accounts for at least one half of the total G at failure. Hence, it is the mode I and mixed-mode interlaminar fracture toughness data that will be most useful in predicting delamination failure in composite components in service. Although apparent G_{IIC} measurements may prove useful for completeness of generating mixed-mode criteria, the accuracy of these measurements may have very little influence on the prediction of mixed-mode failures in most structural components.

Introduction

One of the most common failure modes for composite structures is delamination. The remote loadings applied to composite components typically get resolved into interlaminar tension and shear stresses at discontinuities that create mixed mode I & II delaminations. Over the past 10-20 years, it has become accepted practice to characterize the onset and growth of these mixed-mode delaminations using fracture mechanics. The strain energy release rate, G , and the mode I component due to interlaminar tension, G_I , and mode II component due to interlaminar shear, G_{II} , are calculated using the virtual crack closure technique[1]. In order to predict delamination onset or growth, these calculated G components are compared to interlaminar fracture toughness properties measured over a range from pure mode I loading to pure mode II loading.

Examples of mixed-mode delamination criteria for carbon fiber reinforced composites with either a brittle epoxy (AS4/3501-6) or a toughened epoxy matrix (IM7/E7T1-2), are shown in figures 1a and 1b, respectively [2,3]. The critical G for delamination is plotted as a function of the mode II percentage compared to the total G . Hence, at $G_{II}/G = 0$, the loading at the delamination front is a pure opening mode I, whereas at $G_{II}/G = 1$, the loading at the delamination front is a pure shear mode II. As figure 1 indicates, the apparent mode II toughness for a graphite epoxy material is typically much greater than the mode I toughness and has significantly more variability or scatter. In this paper, some of the reasons for the differences in magnitude and scatter between G_{Ic} and G_{IIc} will be examined. The significance of these differences on the prediction of mixed-mode delamination in composite structural configurations will be discussed.

Background

In the 1950's, Irwin proposed a general theory of fracture [4,5], based on the method of Westergaard [6], that postulated the existence of three unique fracture modes that could occur at the tip of a crack (fig. 2). These fracture modes included: (1) an opening mode I, where the crack faces underwent opening displacements relative to one another as the crack grew, (2) an in-plane sliding

shear mode II, where the crack faces slid over one another in the direction of the crack growth, and (3) an out-of-plane scissoring (or tearing) mode III where the crack faces slid relative to one another in a direction normal to the direction of crack growth. The elasticity solution for stress intensity factors associated with these three postulated fracture modes (K_I, K_{II}, K_{III}) were derived yielding a mathematically complete and consistent theory for fracture of materials and structures. Strain energy release rates may be related to these stress intensity factors squared through coefficients consisting solely of material properties. Solutions for cracked bodies with specific configurations and loadings were developed and applied to structural problems [7]. However, most of these problems consisted of cracks in homogeneous materials (typically structural metallic materials) where cracks that may originally have all three fracture modes when loaded would typically turn immediately as the crack grew to assume a pure opening mode I orientation. Hence, the resistance of these materials to fracture could be adequately described in terms of the opening mode fracture toughness, K_{Ic} , alone.

With the advent of adhesively bonded structures and laminated composite materials in the 1960's and 1970's, the problem of debonding of adhesive bonds, and delamination in composite materials, created a class of problems where cracks were constrained to grow in bond lines, or resin rich regions between composite plies, such that macroscopically the cracks could not assume a pure opening mode I orientation. Therefore, for this class of materials, the mixed-mode fracture problem that was resolved mathematically in the 1950's posed a challenge in terms of fracture toughness characterization.

The opening mode I characterization proved relatively straight forward with the advent of the Double Cantilever Beam (DCB) test configuration, although complexities involving the influences of bondline and insert thicknesses, precracking techniques, and fiber bridging in composites delayed the standardization of this test method until the 1990's [8,9]. Development of test methods for characterizing the interlaminar shear fracture toughness, however, has proven to be a difficult task, both in terms of achieving an adequate configuration to yield a pure shear loading at the crack tip, and in the interpretation of the test results [10]. It is the latter issue that will be the focus of this paper. As Shakespeare might

have said, at issue is whether G_{IIc} is to be, or not to be, considered a generic property of the composite material. Since most of the data generated to date has been for the sliding shear mode II fracture, the discussion will be limited to the measurement and interpretation of G_{IIc} .

Mode II Fracture Toughness measurement results

In the 1980's several test methods were proposed for measuring G_{IIc} . However, to-date none of these have been standardized. The most popular methods are the End-notched Flexure (ENF) and End-loaded split beam (ELS) shown in figure 3. The ENF test involves a simple three point bend loading, but it results in an unstable delamination growth unless the initial crack is very long [11] or the test is controlled with a special shear displacement gage [12]. The ELS test involves a more complicated clamped boundary condition but results in a stable delamination growth [13]. Both of these test configurations have been analyzed and have been demonstrated to yield a pure sliding shear fracture mode II at the delamination front [13,14] .

Several interlaboratory "round robin" test programs have been conducted using both of these test methods [3,10]. However, interpretation of the test results has proven to be difficult to resolve. This difficulty may be illustrated by examining some typical results found in the literature [2,3,15-34]. For this review, papers were chosen that compared the influence of precracking versus testing from the embedded insert on G_{IIc} values measured on the same specimen. In addition, papers were chosen that reported the ratio of precracked, or insert, G_{IIc} values to G_{IIc} values measured only from the insert to avoid the complication due to fiber bridging. These data are summarized in Table 1.

Mode II Precracking Effects

One difficulty in measuring the interlaminar shear fracture toughness is the apparent inconsistency between G_{IIc} values measured by growing the crack from a thin midplane insert versus G_{IIc} values measured by growing the crack from an initial shear precrack. For G_{IIc} values measured using the DCB test, a single generic

toughness value may be obtained as the insert thickness is decreased [24], thereby achieving a composite material property where the insert successfully simulates an initial delamination crack without having to resort to precracking which induces fiber bridging. However, G_{IIC} values decrease with insert thickness, but never reach a single value that may be considered a generic property of the composite material [24]. Furthermore, G_{IIC} values measured from the insert are sometimes greater, and sometimes less than, G_{IIC} values measured from a shear precrack. Figure 4 compares results from studies where G_{IIC} values were determined from both the insert and from precracking on the same specimen. In most cases the precrack value is lower than the insert value. However, for two materials (S2/SP250 glass epoxy and IM7/F3900 graphite epoxy) the reverse was true.

G_{IIC} Comparison to G_{IC}

One result that is consistent in the literature for composite materials over a large range of toughnesses is that G_{IIC} always exceeds G_{IC} . Figure 5 shows a plot of the ratio of G_{IIC} to G_{IC} for composite materials with a large range of opening mode interlaminar fracture toughnesses. There is a general trend that the more brittle materials (lower G_{IC} values) have G_{IIC} values that are much greater than the corresponding G_{IC} , whereas the tougher matrix materials (higher G_{IC} values) have G_{IIC} values that are close to, but still greater than, the corresponding G_{IC} .

Some other interesting trends are noted when the total data set in figure 5 is separated into two plots, one for relatively brittle thermoset (epoxy) matrix composites (figure 6) and the rest for relatively tough thermoplastic matrix composites, which for this literature search consisted solely of AS4/PEEK (figure 7). The G_{IIC}/G_{IC} ratios for the epoxy matrix composite materials all exceeded 2 to 1, which gives some credence to the mechanistic fracture theory of reference 35 (described in a later section) as an explanation of a lower bound for G_{IIC} values. However, for all but one of the results in the literature for the tough thermoplastic composite (AS4/PEEK), the G_{IIC}/G_{IC} ratios range between 2 to 1 and 1 to 1. Hence, the micromechanisms at the delamination front may be quite different for these two classes of materials.

Mode II Fracture Mechanisms

Figure 8 compares scanning electron microscope (SEM) photographs of mode I and mode II fracture surfaces for a brittle T300/5208 graphite epoxy composite [22]. For the brittle epoxy material, the mode I fracture surface appears to have a fairly clean cleavage plane, whereas the mode II fracture surface exhibits a very rough fracture plane with the characteristic "hackles" observed in mode II delamination [16,20,22,33,36]. The sketch in figure 8 under the mode II SEM image illustrates the principal tension stress at a 45 degree angle to the delamination plane that results from mode II loading and is responsible for creating tension microcracks in the resin rich region between plies. Once these cracks appear, the ligaments formed by them are forced to bend until they fracture and coalesce, creating the perceived extension of the original delamination via mode II. Figure 9 shows an edge view generated by in-situ testing in a scanning electron microscope [36] that illustrates the formation and coalescence of microcracks forming the final interlaminar shear fracture surface.

Figure 10 compares SEM photographs of mode I and mode II fracture surfaces for a tough AS4/PEEK graphite thermoplastic composite. In contrast to the brittle composite, for the tough thermoplastic matrix composite both the mode I and II fracture surfaces are similar, with extensive evidence of matrix yielding at the delamination front.

In both the brittle and tough matrix composite materials, the complex failure process under mode II loading is far removed from the idealized sliding of two crack planes relative to one another as postulated in the fracture mechanics elasticity solutions. Hence, a mechanistic explanation of mode II fracture is needed.

Mode II Fracture Theory

In reference 35, a fracture mechanics based failure criteria was postulated based on the observation that for brittle homogeneous materials subjected to mixed-mode loading, "fracture occurs when the total mode I component which is experienced is equal to a critical value, G_0 ." This idea was expressed mathematically as

$$G_I + \sin^2\omega G_{II} = G_0 \quad (1)$$

where ω corresponds to "the slope of the surface roughness." A worse case was postulated for omega of 45 degrees corresponding to the "shear microcracks that form ahead of the main crack" in a composite interface that is delaminating. The authors noted that if $G_{II} = G_{IIc}$ when $G_I = 0$, then

$$\sin^2\omega = G_{Ic}/G_{IIc} \quad (2)$$

Equation 2 implies that G_{IIc} may be estimated based on a measured G_{Ic} and omega, which if assumed to be the worst case of 45 degrees, would yield a maximum value of G_{IIc} equal to twice G_{Ic} . This is consistent with the initial damage mechanism postulated in the previous section, i.e. the formation of tension microcracks ahead of the delamination front. However, it does not account for the bending and fracture of the ligaments formed by the microcracks that releases much of the energy required to create the perceived macroscopic mode II delamination growth. Indeed, the authors cited an epoxy matrix composite example where $G_{IIc} = 2.22 G_{Ic}$. Further examples from the literature, as summarized in figure 5, also yield G_{IIc} values much greater than twice the corresponding G_{Ic} . Hence, the basic premise set forth in reference 35 was sound, i.e., that the actual failure mechanism is due to tension, but a complete description of failure was missing. Therefore, equation (2) at best represents only a lower bound on G_{IIc} .

The theory postulated in reference 35 implies that the macroscopic shear fracture corresponds to the growth of the tension microcrack as an extension of the initial delamination due to the mode I component of the mixed mode loading at the delamination front. For composite delamination under shear loading, however, a more realistic sequence of failure may be as follows: (1) a tension microcrack initiates ahead of the original delamination front wherever the weakest flaw exists in the resin rich layer ahead of the crack and forms at a 45 degree angle to the original delamination, (2) further microcracks accumulate in front of the initial microcrack, with a spacing defined by classical shear lag considerations and the distribution of inherent flaws in the ply

interface, and (3) these microcracks finally coalesce to form an extension of the delamination.

For the initial tension microcracking, a transverse tension strength criteria, using Weibull statistics to characterize the flaw sensitivity [37], may prove useful. This may also help to account for the increased scatter in mode II toughness values compared to mode I values as shown in figure 1. In fact, it may be argued that the transverse tension strength and mode I interlaminar fracture toughness are the only true generic material properties that control the failure of a brittle material.

Beyond the initiation phase, however, a complex model of ligament bending and fracture for brittle materials, and ligament bending, yielding, and rupture for ductile materials, would be needed to adequately characterize the actual failure mechanism at the delamination front under mode II loading. Such a model was recently proposed to account for this sequence of events [38]. The model was based on an adhesive bond containing a crack analogous to the composite delamination in the resin rich layer between plies. A shear lag model was utilized to predict a regular spacing of microcracks ahead of the delamination front that depended on the opening mode fracture toughness of the resin, the shear modulus and yield strength of the resin, and the thickness of the resin rich layers between the plies. A quantitative relationship was derived relating these constituent properties to the apparent composite G_{IIc} by utilizing a curve fitting parameter, m , determined by plotting the effective shear modulus of the resin layer with multiple matrix cracks as a function of the crack spacing normalized by the resin layer thickness.

Although this model provides some useful insights into the relative influence of constituent properties on the apparent composite G_{IIc} , the predicted toughness is very sensitive to the curve fitting parameter chosen. Even if a model could be developed without introducing a new curve fitting parameter, it would be difficult to demonstrate its value as a predictive tool because of the extreme variability of apparent G_{IIc} values relative to corresponding G_{Ic} values (figure 5). In addition, requiring a local characterization of the material, i.e., measuring transverse tension strength, resin fracture toughness, resin moduli, resin tension and yield strengths, etc. needed for modeling crack tip micromechanisms discretely will be extremely labor intensive compared to simply measuring the

apparent G_{IIc} . Furthermore, experience with mixed-mode delamination failures that occur in structural configurations under realistic loadings typically result in problems where the mode I component is predominant, as illustrated in the next section.

Relevance to Mixed-mode Delamination Onset Prediction

Since the mid 1970's, several strain energy release rate solutions have been developed for delaminations in flat uniform thickness composite laminates and in more realistic structural configurations (such as tapered, curved, and stringer reinforced laminates) where failures have been experimentally documented. These studies all seem to indicate that it is the G_I component that controls the onset of delamination much more than the G_{II} component.

Initial studies on edge delamination of flat laminates with straight edges indicated that the onset of delamination depended strongly on the stacking sequence. Stacking sequences having large G_I components associated with delamination prone interfaces yielded lower failure strains at delamination onset [39]. Failure occurred when the mode I component reached G_{Ic} for the composite regardless of the G_{II} component. Flat laminates with open holes, modeled as a series of laminates with varying layups using a rotated straight edge concept, yielded similar results where the G_I component appeared to control the onset of delamination around the hole boundary [40].

Recently, a number of studies have begun to appear in the literature for a variety of more typical structural configurations. These include studies on tapered laminates containing internal ply drops to vary thickness [41-43], curved laminates [44,45], and stringer reinforced laminates subjected to out-of-plane "pull-off" loading [46,47]. The material, configuration, and mixed-mode ratio (G_{II}/G) for these studies is summarized in Table 2. In the majority of these cases, the failure occurs at a location where the G_I component accounts for at least one half of the total G at failure, i.e., where G_{II}/G is less than 50%. Indeed, for the tapered and curved laminates studied, G_{II}/G never exceeded 10%.

In addition to these models of complex loadings on structural components, the problem of delamination resulting from low velocity impact has been shown to consist of a sequence of events beginning with a matrix crack induced by transverse shear (principle

tension stresses at 45 degrees to the laminate axis) followed by a mixed mode I & II delamination [48]. Hence, the typical assumption that G_{IIc} is the most important parameter for characterizing low velocity impact damage [38] is questionable.

These structural configuration case studies indicate that the mode I and mixed-mode interlaminar fracture toughness data will be most useful in predicting delamination failure in composite components in service. Even though the apparent G_{IIc} values will typically be measured for completeness of generating the mixed-mode criteria illustrated in figure 1, the accuracy of these measurements may have very little influence on the prediction of mixed-mode failures in most structural components.

Summary

The concept of G_{IIc} as a measure of the interlaminar shear fracture toughness of a composite material was critically examined. An extensive literature review was conducted to identify studies where Mode I and Mode II fracture toughness measurements were compared. This review indicated that for composite materials over a large range of toughnesses, G_{IIc} always exceeds G_{Ic} . In addition, the more brittle materials had G_{IIc} values that were often much greater than the corresponding G_{Ic} , whereas the tougher matrix materials had G_{IIc} values that are close to, but still greater than, the corresponding G_{Ic} . However, it was noted that G_{IIc} values measured from the insert are sometimes greater, and sometimes less than, the G_{IIc} values measured from a shear precrack. Furthermore, examination of the micromechanisms at the tip of the delamination front documented in the literature for a wide range of composite materials, indicated that interlaminar shear failure actually consists of tension failures, followed by the coalescence of ligaments created by these failures, and not the sliding of two planes relative to one another that is assumed in fracture mechanics theory. Hence, the apparent G_{IIc} as typically measured is inconsistent with the original definition of shear fracture.

For the initial tension microcracking, a transverse tension strength criteria, using Weibull statistics to characterize the flaw sensitivity, may help to account for the increased scatter in mode II toughness values compared to mode I. Beyond the initiation phase, however, a complex model of ligament bending and fracture for

brittle materials, and ligament bending, yielding, and rupture for ductile materials, would be needed to adequately characterize the actual failure mechanism at the delamination front under mode II loading. Even if this could be achieved, it would be of questionable value because of the extreme variability of apparent G_{IIc} values relative to corresponding G_{Ic} values. In addition, requiring a local characterization of the material needed for modeling crack tip micromechanisms discreetly will be extremely labor intensive compared to simply measuring the apparent G_{IIc} .

Several strain energy release rate solutions have been developed for both composite laminates and structural components where failures have been experimentally documented. In the majority of these cases, the failure occurs at a location where the mode I component accounts for at least one half of the total G at failure. Hence, it is the mode I and mixed-mode interlaminar fracture toughness data that will be most useful in predicting delamination failure in composite components in service. Although apparent G_{IIc} measurements may prove useful for completeness of generating mixed-mode criteria, the accuracy of these measurements may have very little influence on the prediction of mixed-mode failures in most structural components. Therefore, as Shakespeare might have said, the controversy over mode II fracture toughness measurement may turn out to be much ado about nothing.

References

1. Rybicki, E.F. and Kanninen, M.F., "A Finite Element Calculation of Stress Intensity Factors by a Modified Crack Closure Integral," Engineering Fracture Mechanics, Vol.9, 1977, pp.931-938.
2. Reeder, J.R., "A Bilinear Failure Criterion for Mixed-Mode Delamination," in Composite Materials: Testing and Design, Eleventh Volume, ASTM STP 1206, Dec. 1993, pp. 303-322.
3. Murri, G.B., Reeder, J.R., and Li, J. : ASTM Subcommittee D30.06 Interlaboratory round robin test data, 1996.
4. Irwin, G.R. "Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate," Transactions of ASME J. of Applied Mechanics, 1957.
5. Irwin, G.R., "Fracture Mechanics," Structural Mechanics, Pergamon Press, New York, NY,1960.
6. Westergaard, H.M., "Bearing Pressures and Cracks," Transactions of ASME J. of Applied Mechanics, 1939.
7. Paris, P.C. and Sih, G.C., "Stress Analysis of Cracks," in Fracture Toughness Testing and its Applications, ASTM STP 381, June, 1964, pp.30-83.
8. O'Brien, T. K. and Martin, R.H. : Round Robin Testing for Mode I Interlaminar Fracture Toughness of Composite Materials, Journal of Composites Technology and Research, Vol. 15, No. 4, Winter 1993, pp.269-281.
9. Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites,' ASTM Standard D 5528-94a, ASTM Annual Book of Standards, Vol. 15.03, 1994, pp. 272-281.
10. Davies, P., Ducept, F., Brunner, A.J., Blackman, B.A.K., deMorais, A.B., "Development of a Standard Mode II Shear Fracture Test Procedure," Proceedings of the Seventh European Conference on Composite Materials (ECCM-7), Vol.2, Third Symposium on Composite Testing and Standardization (ECCM-CTS-3), London, May, 1996, Woodhead Publishers, Ltd., Cambridge, p.9-15.

11. Russell, A.J., "On Measurement of Mode II Interlaminar Fracture Energies," Defence Research Establishment Pacific (DREP) Victoria, British Columbia, Canada, Materials Report, 82-0, Dec. 1982.
12. Kageyama, K., Kikuchi, M., and Yanagisawa, N., "Stabalized End Notched Flexure Test: Characterization of Mode II Interlaminar Crack Growth," in Composite Materials: Fatigue and Fracture, Third Volume, ASTM STP 1110, Sept. 1991, pp. 210-225.
13. Davies, P., Moulin, C., Kausch, H.H., Fischer, M., "Measurement of G_{Ic} and G_{IIc} in carbon/epoxy composites ," Composite Science and Technology, Vol.39, 1990, p.193-205.
14. Salpekar, S. A.; Raju, I. S.; and O'Brien, T. K.: Strain Energy Release Rate Analysis of the End-Notched Flexure Specimen Using the Finite Element Method. ASTM Journal of Composites Technology and Research , Vol. 10, No. 4, Winter 1988, pp. 133-139.
15. Hashemi,S., Kinloch,A.J., and Williams, J.G. "The Analysis of Interlaminar Fracture in Uniaxial Fibre-polymer Composites," Proceedings of the Royal Society of London, Vol. A427, 1990, pp.173-199.
16. Russell, A.J. and Street, K.N., "Moisture and Temperature Effects on the Mixed-Mode Delamination Fracture of Unidirectional Graphite Epoxy," in Delamination and Debonding of Materials, ASTM STP 876, Oct. 1985, pp. 349-370.
17. Bradley,W.L. and Cohen, R.N., "Matrix Deformation and Fracture in Graphite Reinforced Epoxies," in Delamination and Debonding of Materials, ASTM STP 876, Oct. 1985, pp. 389-410.
18. Russell, A.J. and Street, K.N., "The Effect of Matrix Toughness on Delamination: Static and Fatigue Fracture under Mode II Shear Loading of Graphite Fiber Composites," in Toughened Composites, ASTM STP 937, May 1987, pp. 275-294.
19. Davies, P., and de Charentenay, F.X., "The Effect of Temperature on the Interlaminar Fracture of Tough Composites," Proceedings of the Sixth International Conference on Composite Materials (ICCM VI), Vol.3, July, 1987, pp. 284-294.

20. Corleto, C.R. and Bradley, W.L., "Mode II Delamination Fracture Toughness of Unidirectional Graphite/Epoxy Composites," in Composite Materials: Fatigue and Fracture, Second Volume, ASTM STP 1012, April, 1989, pp. 201-221.
21. Prel, Y.J., Davies, P., Benzeggagh, M. and de Charentenay, F.X., "Mode I and Mode II Delamination of Thermosetting and Thermoplastic Composites," in Composite Materials: Fatigue and Fracture, Second Volume, ASTM STP 1012, April, 1989, pp. 251-269.
22. O'Brien, T.K. ; Murri, G.B. ; and Salpekar, S. A. "Interlaminar Shear Fracture Toughness and Fatigue Thresholds for Composite Materials," in Composite Materials: Fatigue and Fracture, Second Volume, ASTM STP 1012, April, 1989, pp. 222-250.
23. Russell, A.J., "Initiation and Growth of Mode II in Toughened Composites," in Composite Materials: Fatigue and Fracture, Third Volume, ASTM STP 1110, Sept., 1991, pp. 226-242.
24. Murri, G.B. and Martin, R.H., "Effect of Initial Delamination on Mode I and Mode II Interlaminar Fracture Toughness and Fatigue Fracture Thresholds," in Composite Materials: Fatigue and Fracture, Fourth Volume, ASTM STP 1156, June 1993, pp. 239-256.
25. Hooper S.J. and Subramanian, R., "Effects of Water and Jet Fuel Absorbtion on Mode I and Mode II Delamination of Graphite/Epoxy," in Composite Materials: Fatigue and Fracture, Fourth Volume, ASTM STP 1156, June 1993, pp. 318-340.
26. Sriram, P., Khourchid, Y., Hooper, S.J., and Martin, R.H., "Experimental Development of a Mixed-Mode Fatigue Delamination Criterion," in Composite Materials: Fatigue and Fracture, Fifth Volume, ASTM STP 1230, Oct. 1995, pp. 3-18.
27. Kageyama, K., Kimpara, I., Ohsawa, I., Hojo, M., and Kabashima, S., "Mode I and Mode II Delamination Growth of Interlayer Toughened Carbon/Epoxy Composite System," in Composite Materials: Fatigue and Fracture, Fifth Volume, ASTM STP 1230, Oct. 1995, pp. 19-37.
28. Steinmetz, G.G., and Arendts, F.J., "Mixed-Mode Interlaminar Fracture Testing using the MMB-Fixture," "Proceedings of the Tenth International Conference on Composite Materials (ICCM X), Vol.I, August, 1995, pp. 165-172.

29. Kussmaul K. and Alberti, M.v., "On the Delamination Behaviour of Carbon Fibre Reinforced Plastics under Mixed-Mode Fatigue Loading," Proceedings of the Tenth International Conference on Composite Materials (ICCM X), Vol.1, August, 1995, pp. 125-132.
30. Tanaka, K., Kageyama, K., and Hojo, M., "Standardization of Mode I and II Interlaminar Fracture Toughness Tests for CFRPs in Japan," Proceedings of the Second European Conference on Composites Testing and Standardisation (ECCM-CTS-2), Hamburg, Germany, Sept. 1994, pp. 533-541.
31. Davies, P., Benzeggagh, M. L. and de Charentenay, F.X., "The Delamination Behavior of Carbon Fiber Reinforced PPS", Proceedings of the 32nd International SAMPE Symposium, Anaheim, CA, April, 1987, pp. 134-146.
32. Hashemi,S., Kinloch,A.J., and Williams, J.G. "Mechanics and Mechanisms of Delamination in a Poly(ether sulphone)-Fibre Composite", Composites Science and Technology, Vol.37, No.4, 1990, pp.429-462.
33. Hibbs, M.F. and Bradley, W.L., "Correlations Between Micromechanical Failure Processes and the Delamination Toughness of Graphite/Epoxy Systems", in Fractography of Modern Engineering Materials, ASTM STP 948, 1987, pp. 68-97.
34. Jurf, R.A., and Pipes, R.B., "Interlaminar Fracture of Composite Materials", J. Composite Materials, Vol. 16, Sept. 1982, pp. 386-394.
35. Charalambides, M., Kinloch, A.J., Wang, Y., and Williams, J.G. "On the Analysis of Mixed-mode Failure," Int. J. of Fracture, Vol.54, 1992, pp.269-291.
36. Corleto, C.R. and Bradley, W.L., "Correspondence Between Stress Fields and Damage Zones Ahead of Crack Tip of Composites under Mode I and Mode II Delamination," Proceedings of the Sixth International Conference on Composite Materials (ICCM VI), Vol.3, July, 1987, pp. 378-387.

37. O'Brien, T. K. and Salpekar, S. A. : Scale Effects on the Transverse Tensile Strength of Graphite Epoxy Composites, Composite Materials: Testing and Design, Eleventh Volume, ASTM STP 1206, December, 1993, pp.23-52.
38. Lee, Shaw Ming : Mode II Delamination Failure Mechanisms of Polymer Matrix Composites. To appear in the Journal of Materials Science, 1996.
39. O'Brien, T. K.: Mixed-Mode Strain-Energy-Release Rate Effects on Edge Delamination of Composites. Effects of Defects in Composite Materials, D. J. Wilkins, ed., ASTM STP 836, 1984, pp.125-142.
40. O'Brien, T. K.; and Raju, I. S.: Strain-Energy-Release Rate Analysis of Delamination Around an Open Hole in a Composite Laminate. Presented at the 25th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, Palm Springs, CA, May 1984. (AIAA-84-0961).
41. Salpekar, S. A.; Raju, I. S.; and O'Brien, T. K.: Strain Energy Release Rate Analysis of Delamination in a Tapered Laminate Subjected to Tension Load. Proceedings of the American Society for Composites Third Technical Conference, Seattle, WA, September 1988, pp. 642-654.
42. Murri, G.B.; O'Brien, T. K.; and Salpekar, S. A.: Tension Fatigue of Glass/Epoxy and Graphite/Epoxy Tapered Laminates, Journal of the American Helicopter Society, Vol. 38, No.1, January, 1993, pp. 29-37.
43. Murri, G.B.; Salpekar, S. A.; and O'Brien, T. K.: Fatigue Delamination Onset Prediction in Unidirectional Tapered Laminates, Composite Materials: Fatigue and Fracture, Third Volume, ASTM STP 1110, September, 1991, pp.312-339.
44. Martin, R.H., "Delamination Failure in a Unidirectional Curved Composite Laminate," Composite Materials: Testing and Design, Tenth Volume, ASTM STP 1120, January, 1992, pp.365-383.
45. Martin, R.H. and Jackson, W.C., "Damage Prediction in Cross-Plied Curved Composite Laminates," Composite Materials: Fatigue and Fracture, Fourth Volume, ASTM STP 1156, June, 1993, pp.105-126.

46. Minguet, P.J, and O'Brien, T.K. : Analysis of Skin/Stringer Bond Failure using a Strain Energy Release Rate Approach; Proceedings of the Tenth International Conference on Composite Materials (ICCM X), Vancouver, British Columbia, Canada, August, 1995, Vol.1, pp.245-252.

47. Li, J., O'Brien, T.K., and Rousseau, C.Q. : Test and Analysis of Composite Hat Stringer Pull-off Test Specimens, Proceedings of the 52nd American Helicopter Society Forum, June 4-6, 1996, Washington, D.C.

48. Salpekar, S.A., "Analysis of Delamination in Cross-Ply Laminates Initiating from Impact Induced Matrix Cracking," ASTM J. of Composites Technology and Research, Vol. 15, No.2, Summer, 1993, pp.88-94.

Table 1 - Mode I & II Interlaminar Fracture Toughness Data

Reference	Material	G_{Ic} , J/m ² (insert)	G_{IIc} , J/m ² (insert)	G_{IIc} , J/m ² (Precrack)
21	T300/914	185	795	598
19	IM6/6376	180	700	
22	T300/BP907	400	1961	1519
17	AS4/3502	227		574
16	AS1-3501-6	132	460	
16	HMS-3501-6	30	170	
3	IM7/E7T1	146	1860	1220
3	IM7/F655	223	1204	660
3	IM7/F3900	571	2090	2571
23	IM6/5245C		979	758
23	IM7/8551-7		1185	1147
29	HTA/6376	360	1440	
28	G30-500/5208	70	400	
25	AS4-3501-6	111		814
26	IM7/8320	286	1243	
26	IM7/5260	315	1692	
27	T800H/3900-2	750	2090	1730
2	AS4-3501-6	80	572	
2	IM7/977-2	283	1419	
30	Toho/Q-1113	131	370	
30	Toho/Q-C134	355	991	
20	AS4/3502	227		574
15	T300/6376C	270	600	
21	Eglass/DGEBA	264	3510	2510
24	S2/SP250	130	600	780
21	AS4/PEEK	1460	4250	2695
22	AS4/PEEK	1262		1586
23	AS4/PEEK		3186	3148
29	AS4/PEEK	1850	2220	
27	AS4/PEEK	1320	2530	2040
2	AS4/PEEK	776		1201
30	AS4/PEEK	1260	1477	
15	AS4/PEEK	1680	1740	
18	AS1-3501-6	110		605
18	AS4/2220-3	160		750
18	AS4/PEEK	1330		1765
33	AS4-3501-6	137	1292	
33	AS4/Dow-P6	165	1806	
33	AS4/Dow-P7	340	1325	
33	AS4/Dow-Q6	848	2836	
32	AS4/PES			1250
31	AS4/PPS	196		933
34	AS1-3501-6			670

Table 2 - Delamination in Composite Structural Configurations

Ref. No.	Configuration	Material	Layup	G_{II}/G , %
41	Tapered Laminate	S2/SP250 Glass-Epoxy	0 and 45 degree plies	0-5
42	Tapered Laminate	S2/SP250 Glass-Epoxy	0 and 45 degree plies	0-5
42	Tapered Laminate	IM6/1827I Graphite-Epoxy	0 and 45 degree plies	0-5
43	Tapered Laminate	S2/SP250 Glass-Epoxy	0 degree plies	0-10
43	Tapered Laminate	S2/CE9000 Glass-Epoxy	0 degree plies	0-10
43	Tapered Laminate	IM6/1827I Graphite-Epoxy	0 degree plies	0-5
44	Curved Laminate	AS4/3501-6 Graphite-Epoxy	0 degree plies	5-10
45	Curved Laminate	AS4/3501-6 Graphite-Epoxy	0 and 90 degree plies	5-10
46	Stringer Reinforced Laminate	IM6/3501-6 Graphite-Epoxy	0, 45, and 90 degree plies	13-40
47	Stringer Reinforced Laminate	IM7/E7T1-2 Graphite-Epoxy	45 degree plies	28-55

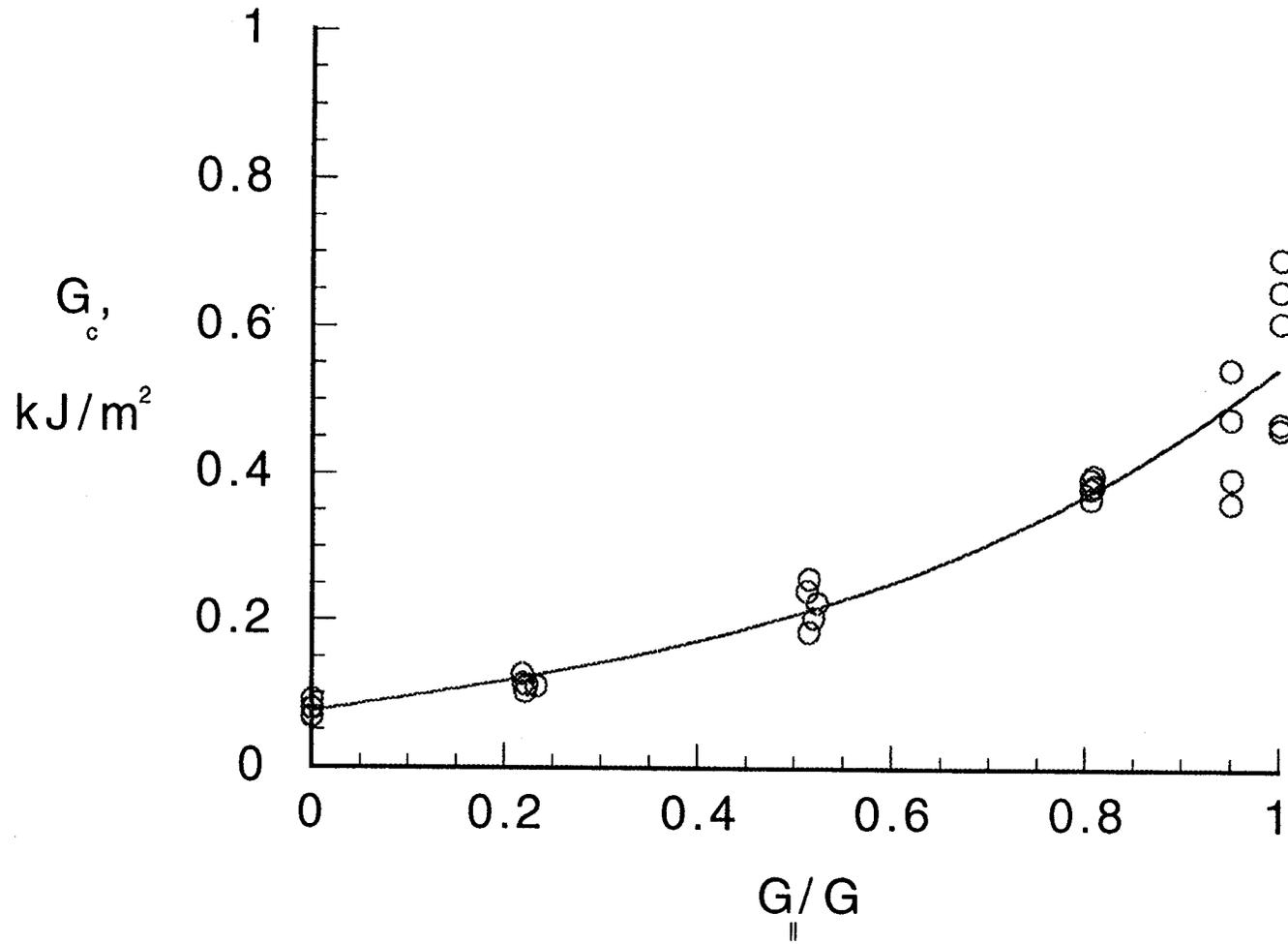


Fig.1a - Mixed Mode Delamination Criterion for AS4/3501-6

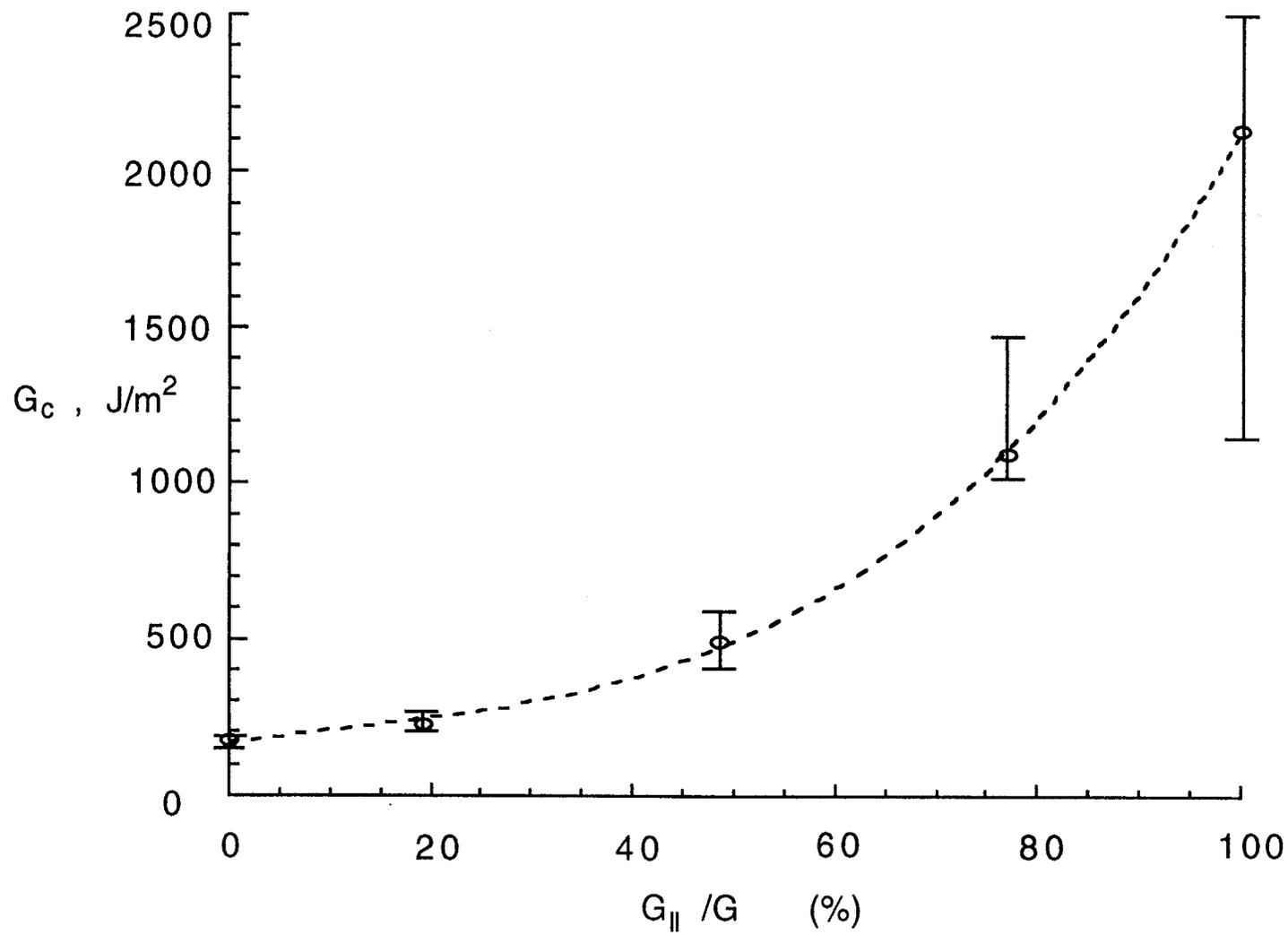
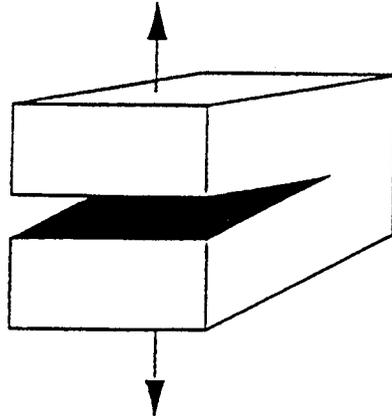
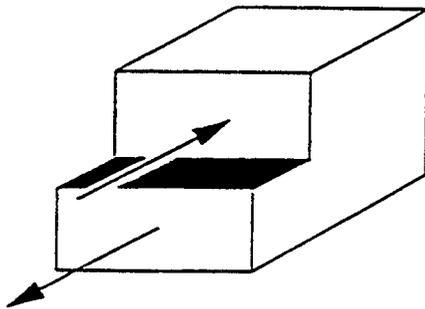


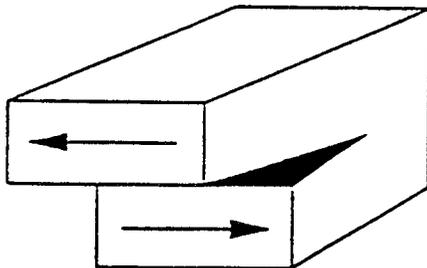
Fig.1b - Mixed Mode Delamination Criterion for IM7/E7T1-2



Mode I
Crack opening or tensile mode



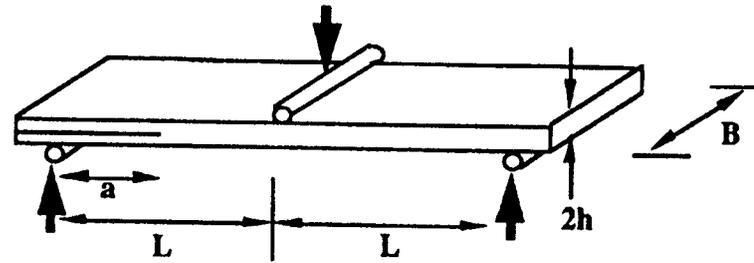
Mode II
In-plane shearing mode



Mode III
Out-of-plane shearing mode

Fig.2 - Fracture Modes

ENF
Test



ELS
Test

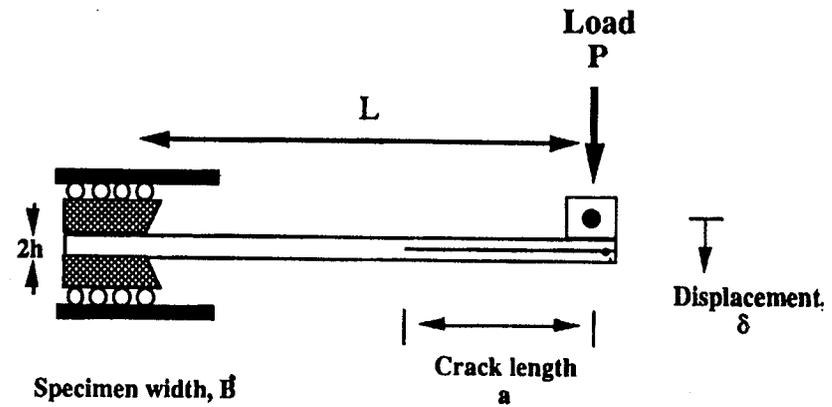


Fig.3 - Mode II Test Configurations

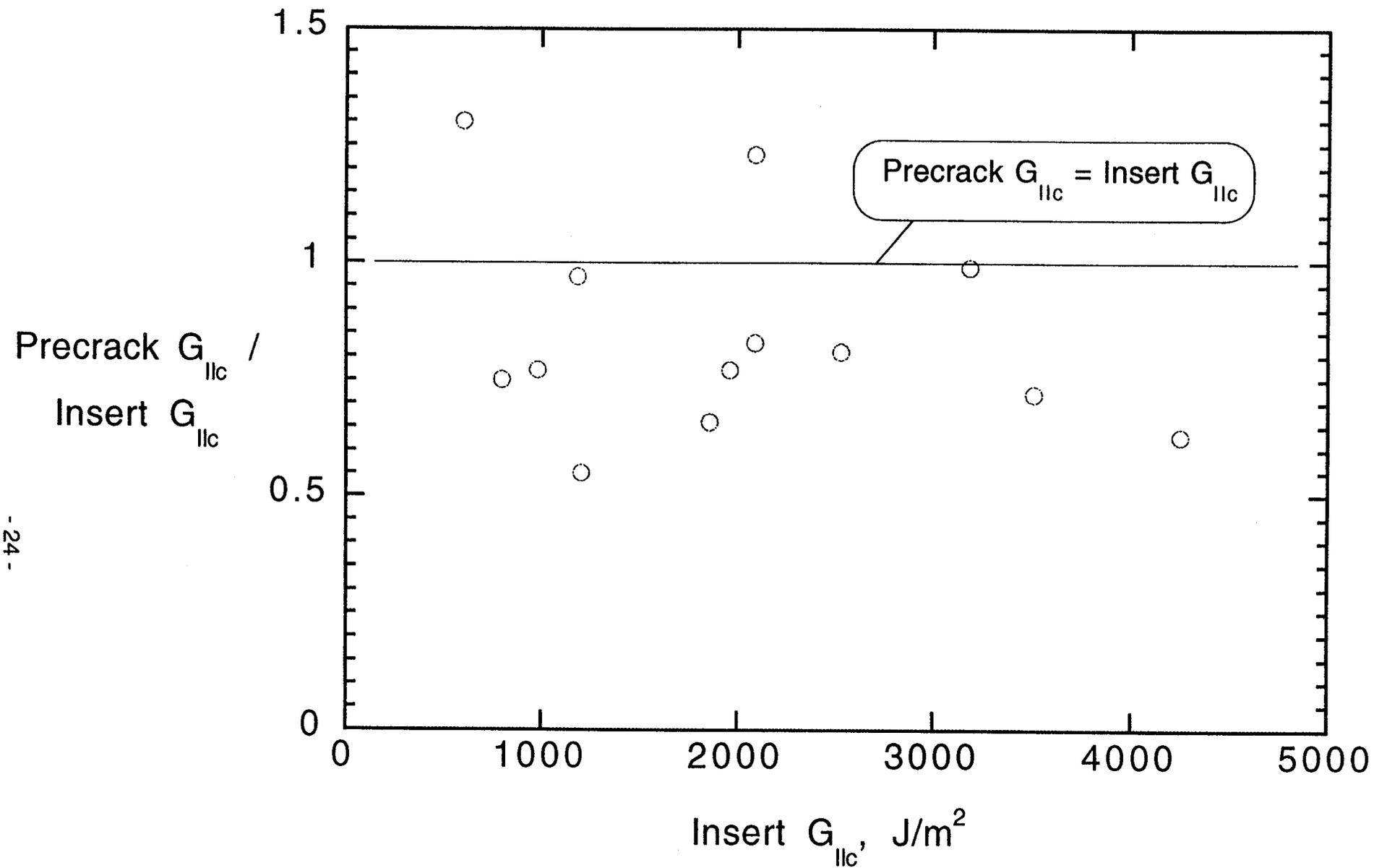


Fig.4 - Ratio of Pre-crack G_{IIc} to Insert G_{IIc} for Polymer Matrix Composites

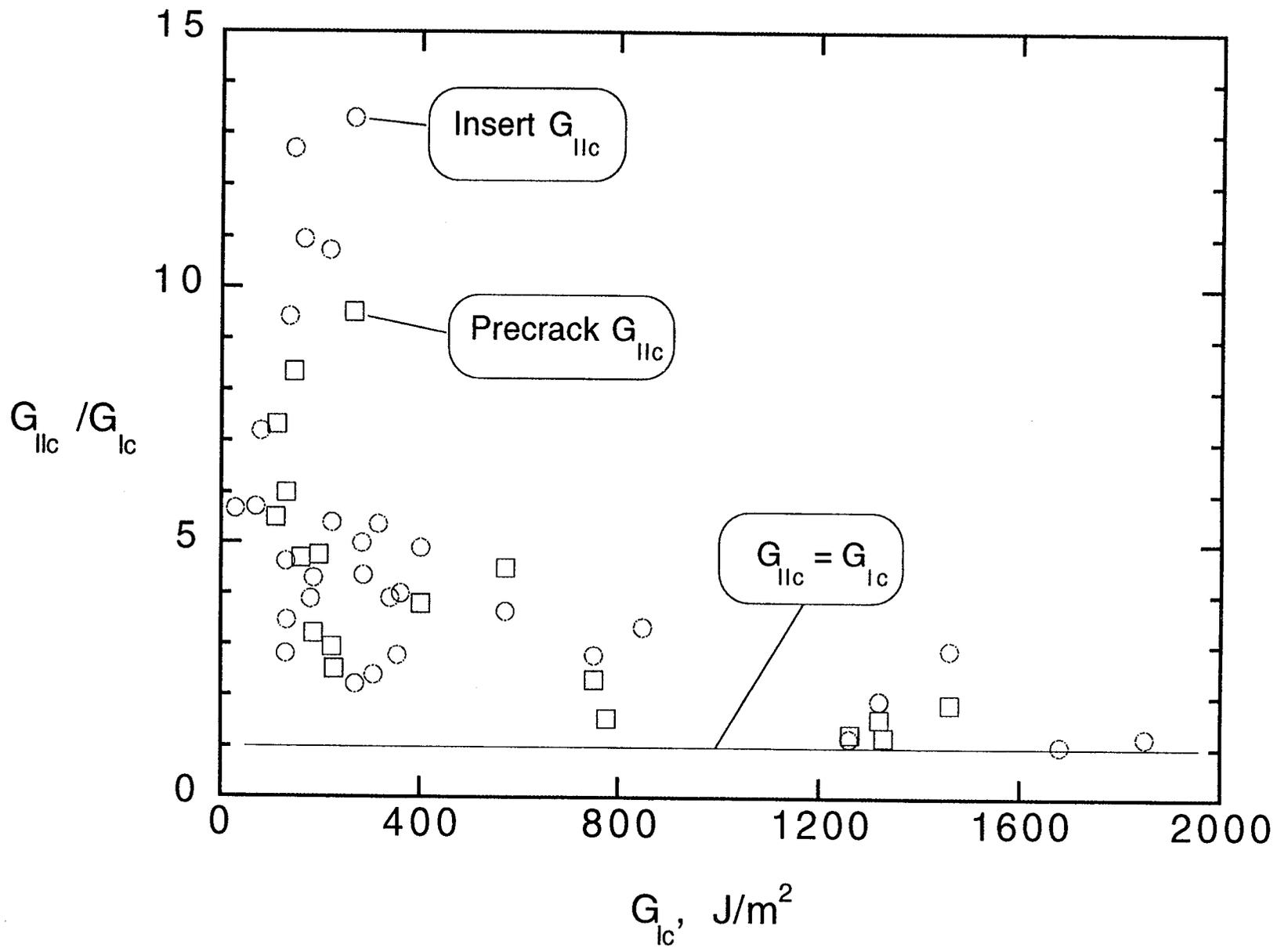
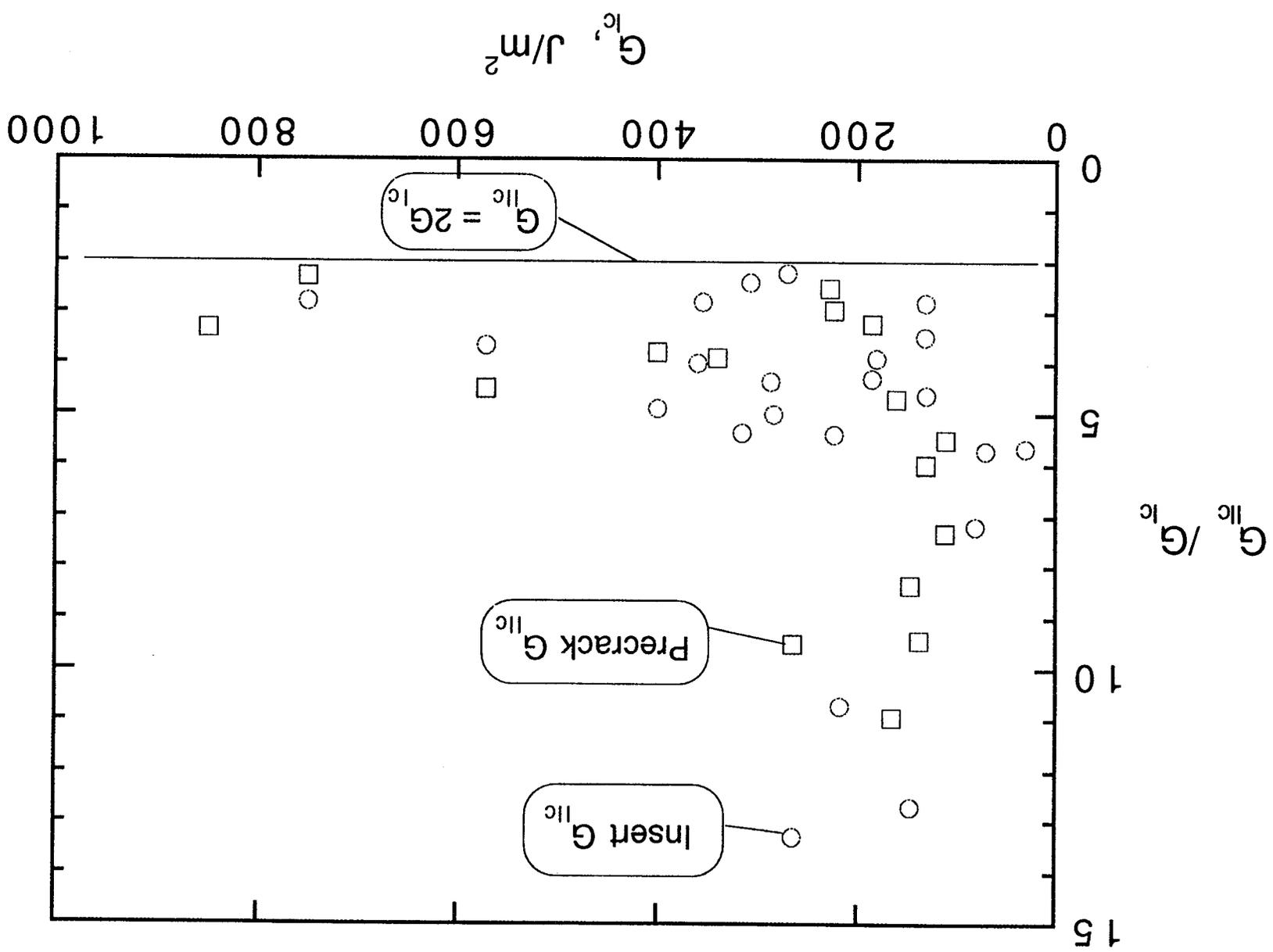


Fig.5 - Ratio of Mode II to Mode I Toughness for Polymer Matrix Composites

Fig.6 - Ratio of Mode II to Mode I Toughness for Graphite and Glass Epoxy Composites



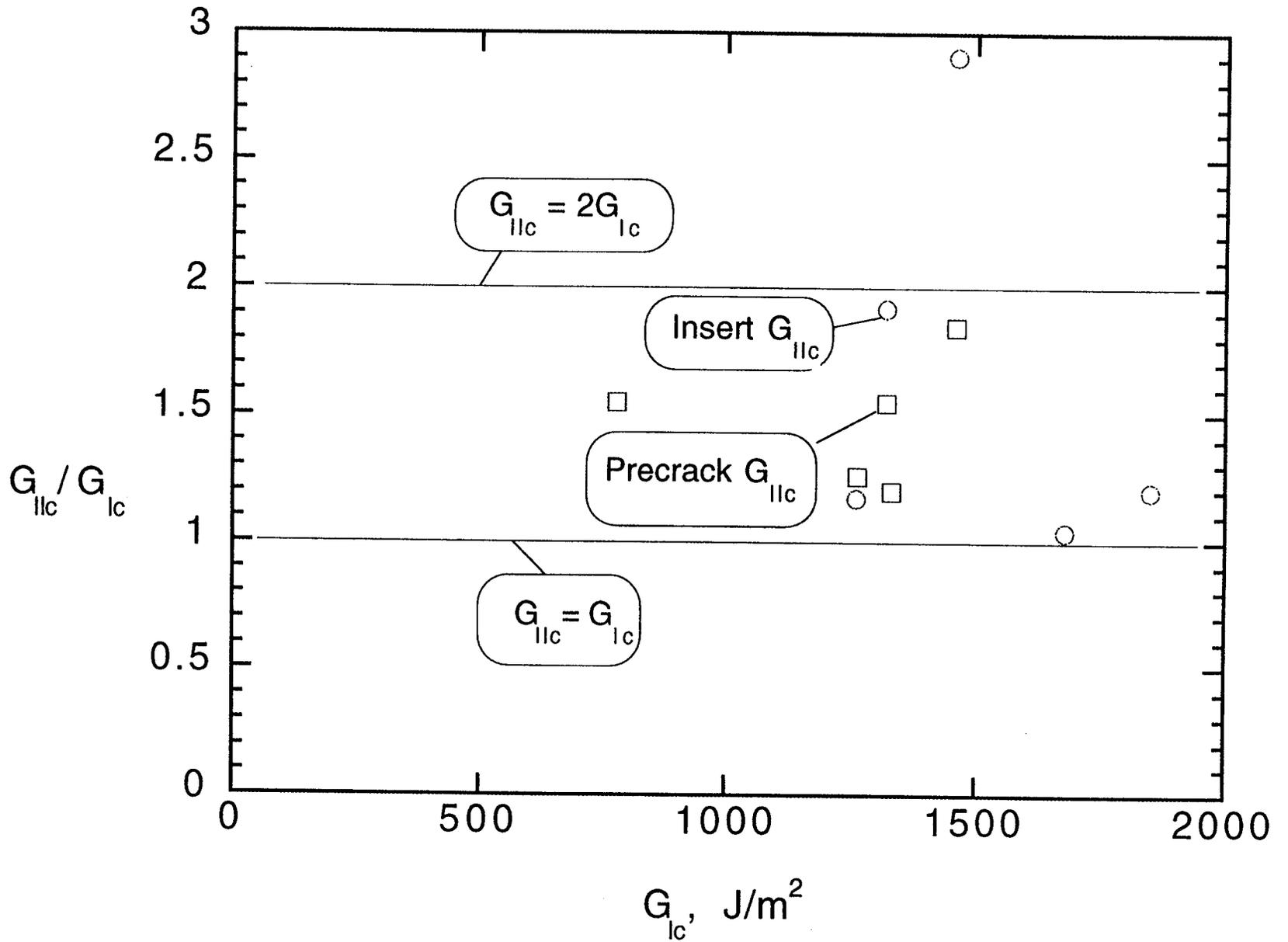


Fig.7 - Ratio of Mode II to Mode I Toughness for AS4/PEEK Composites

Mode I

Mode II

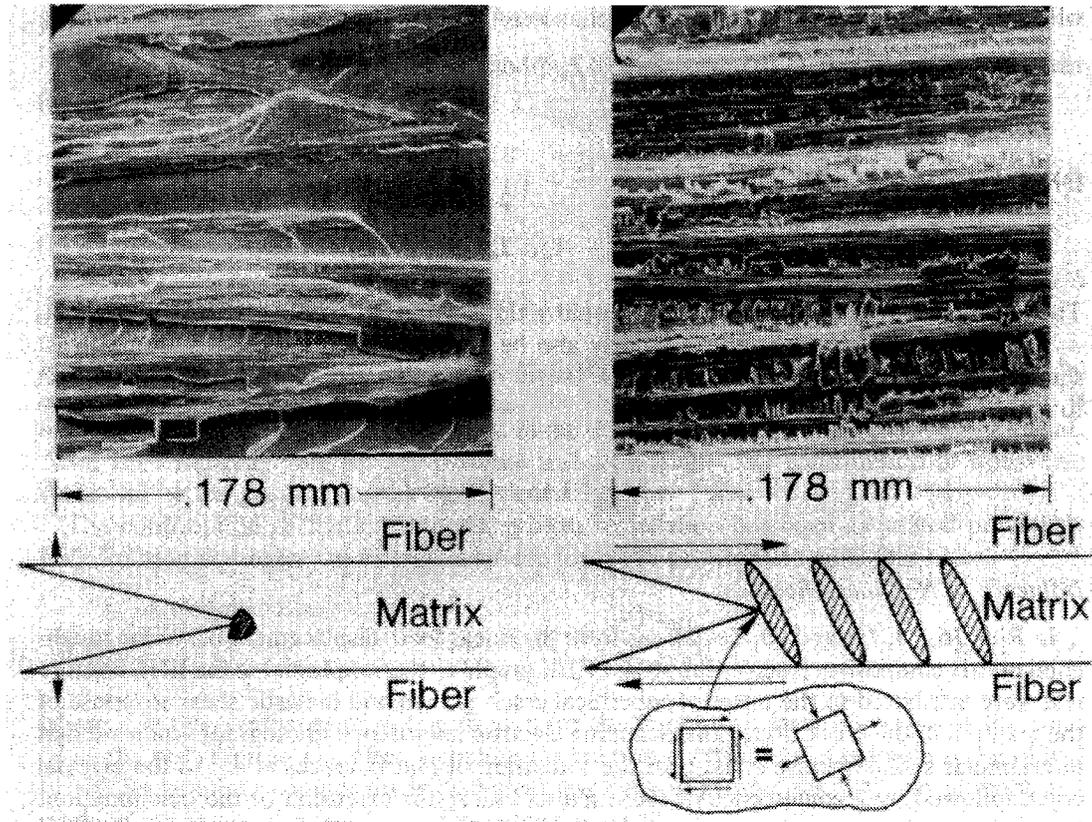
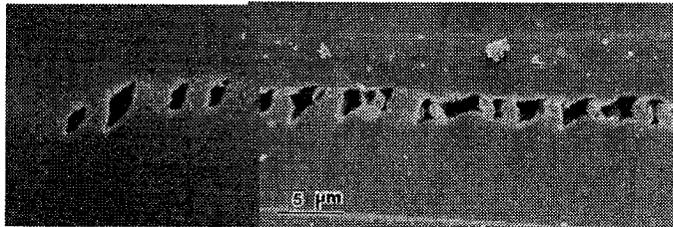
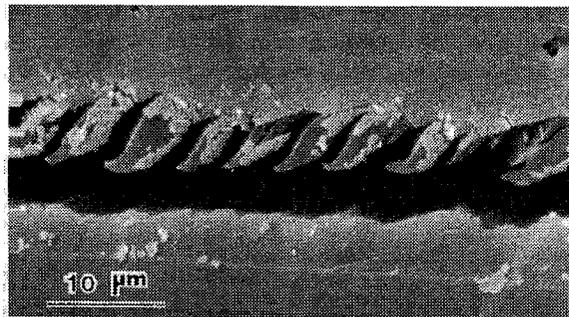


Fig.8 SEM photographs of delamination fracture surfaces in T300/5208 Graphite Epoxy laminates



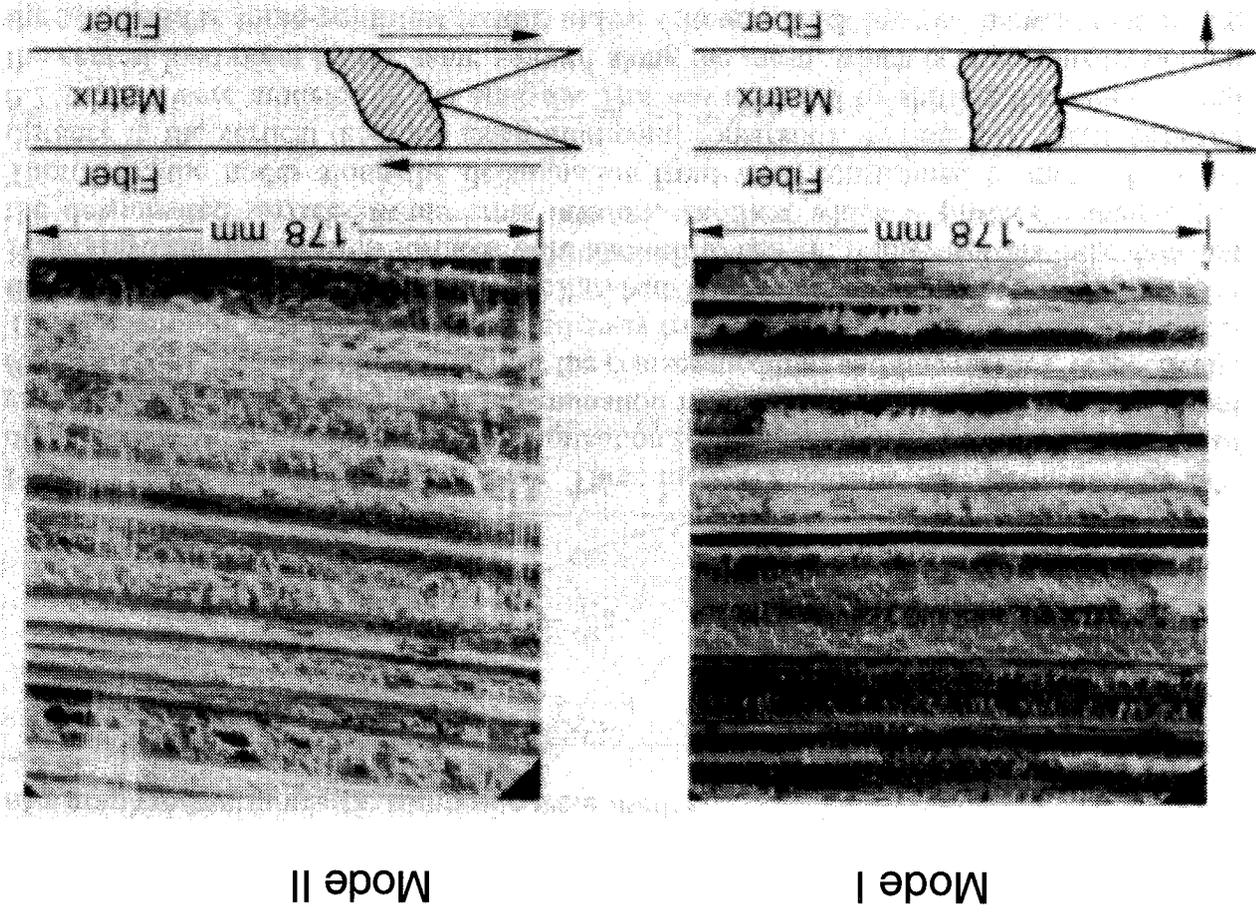
Formation of tension microcracks



Coalescence of microcracks forming hackles

Fig. 9 Formation and Coalescence of Tension Microcracks

Fig.10 SEM photographs of delamination fracture surfaces
in AS4/PEEK laminates



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13. ABSTRACT (Maximum 200 words) The Concept of GIIc as a measure of the interlaminar shear fracture toughness of a composite material is critically examined. In particular, it is argued that the apparent GIIc as typically measured is inconsistent with the original definition of shear failure. It is shown that interlaminar shear failure actually consists of tension failures in the resin rich layers between plies followed by the coalescence of ligaments created by these failures and not the sliding of two planes relative to one another that is assumed in fracture mechanics theory. Several strain energy release rate solutions are reviewed for delamination in composite laminates and structural components where failures have been experimentally documented. Failures typically occur at a location where the mode I component accounts for at least one half of the total G at failure. Hence, it is the mode I and mixed-mode interlaminar fracture toughness data that will be most useful in predicting delamination failure in composite components in service. Although apparent GIIc measurements may prove useful for completeness of generating mixed-mode criteria, the accuracy of these measurements may have very little influence on the prediction of mixed-mode failures in most structural components.				
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